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Computation with Physical Values from Landsat Digital Data

Proper and consistent use of Landsat digital data requires that the digital numbers from computer-compatible tapes be converted to quantitative physical values such as radiance (as measured at satellite altitude) or reflectance of the ground (or albedo of the ground).

ABSTRACT: *Landsat digital images are commonly analyzed by using the digital numbers for each pixel recorded on a computer-compatible magnetic tape. Although this procedure may be satisfactory when only a single, internally consistent image is used, the procedure may produce incorrect results if more than one image is used for analysis as in mosaics or temporal overlays. The digital numbers for each pixel should be converted to their dimensioned equivalents (numbers with physical meaning), such as (1) radiance, as measured at the satellite, in milliwatts per square centimetre per steradian (mW $cm^{-2}sr^{-1}$), or (2) reflectance. These values vary depending on the calibration of the multispectral scanner in each satellite at a given time, the sun angle, the state of the atmosphere, the slope and aspect of the terrain, and surface cover. Atmospheric correction is recognized as vital but is beyond the scope and purpose of this report.*

Equations are given for calculation of radiance and reflectance for the (presently) five radiometric conditions of Landsats 1, 2, and 3, neglecting atmospheric correction. An example is given in which Landsat pixel values derived from different satellites lead to widely differing values of radiance and reflectance. The expression of Landsat data as physical values will reduce errors in the analysis of those data.

INTRODUCTION

LANDSAT digital images in computer-compatible form on magnetic tape are represented by dimensionless digital numbers ranging from 0 to 127 in bands 4, 5, and 6, and 0 to 63 in band 7. The digital numbers are used by numerous investigators to statistically classify cover types in a single image, identify and map terrain features, create continuous images for digital mosaics of several images, ratio spectral bands to eliminate differential illumination effects, and detect changes in successive images of the same area. The results of such analyses may often be incorrect and are imprecise because the digital numbers do not quantitatively represent real physical values and are used only for convenience in computer processing of the data. The purpose of this report is to show that correct and precise results can be obtained by conversion of the digital values to numbers representing physical values as the first step in analysis.

PHYSICAL VALUES OF LANDSAT DIGITAL DATA

The multispectral scanners in Landsats 1, 2, and 3 measure radiation reflected from the Earth's surface in four bands (Table 1).

TABLE 1. LANDSAT REFLECTED RADIATION AND DIGITAL LEVELS

Band	Wavelength	Digital Levels
4	500-600 nanometers (nm)	0-127
5	600-700 nm	0-127
6	700-800 nm	0-127
7	800-1100 nm	0-63

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TABLE 2. RELATIONSHIP BETWEEN OBSERVED SCENE RADIANCE AND DETECTOR SATURATION FOR MULTISPECTRAL SCANNER BANDS 4, 5, 6, AND 7 IN LANDSATS 1, 2, AND 3 IN THE NORMALLY USED LOW GAIN MODE

	Landsat 1		Landsat 2a 6/22/75–7/16/75		Landsat 2b after 7/16/75		Landsat 3a 3/5/78–6/1/78		Landsat 3b after 6/1/78	
Band	L_{min}	L_{max}	L_{min}	L_{max}	L_{min}	L_{max}	L_{min}	L_{max}	L_{min}	L_{max}
4	0	2.48	0.10	2.10	0.08	2.63	0.04	2.20	0.04	2.59
5	0	2.00	0.07	1.56	0.06	1.76	0.03	1.75	0.03	1.79
6	0	1.76	0.07	1.40	0.06	1.52	0.03	1.45	0.03	1.49
7	0	4.00	0.14	4.15	0.11	3.91	0.03	4.41	0.03	3.83

The analysis of the data is usually done on the basis of the digital levels. The levels are related by a linear model (calibration) to the intensity of reflected radiant energy but are not directly comparable among the three satellites because of differences in the calibration of their multi-spectral scanners. In addition, comparison or combination of images taken at different times requires correction for different angles of solar illumination.

The physical values that can be derived from the digital numbers for each band are (1) radiance in milliwatts per square centimetre per steradian (mW $cm^{-2}sr^{-1}$) and (2) reflectance. Calculation of other values may be desirable for specific purposes, but they can all be done by manipulation of these basic physical values.

Radiance in a single band is calculated by

$$\text{Radiance} = \frac{D_n}{D_{max}} (L_{max} - L_{min}) + L_{min}$$

where

D_n = the digital value of a pixel from the computer-compatible tape (CCT);

D_{max} = the maximum digital number recorded on the CCT; 127 in bands 4, 5, and 6, 63 in band 7;

L_{max} = radiance measured at detector saturation in mW $cm^{-2}sr^{-1}$; and

L_{min} = lowest radiance measured by detector in mW $cm^{-2}sr^{-1}$.

Table 2 gives the L_{max} and L_{min} values for Landsats 1, 2, and 3, and for different scanner calibrations at different times. It is taken from the Landsat Data Users Handbook (U.S. Geological Survey, 1979, p. AE-16). The calibrations were changed by NASA/GSFC on the dates given to minimize detector variations within a band. Reflectance in a single band for a Lambertian surface is calculated by

$$\text{Reflectance} = \frac{\pi}{E \sin\alpha} \left[\frac{D_n}{D_{max}} (L_{max} - L_{min}) + L_{min} \right]$$

where

E = irradiance in mW cm^{-2} at the top of the atmosphere:

Band 4 = 17.70 mW cm^{-2}

Band 5 = 15.15 mW cm^{-2}

Band 6 = 12.37 mW cm^{-2}

Band 7 = 24.91 mW cm^{-2}

α = solar elevation, measured from the horizontal, as annotated on Landsat images. (The solar elevation, however, should be calculated for the exact site being studied. Image annotations are shown only to the nearest degree and they may be as much as 1.5° off.)

These two parameters, radiance and reflectance, are physical values that not only are correct in a physical sense but are more understandable to the

TABLE 3. DIGITAL AND PHYSICAL VALUES AND RATIOS OF ADJACENT BANDS

	Digital Values		Radiance		Reflectance	
	D_n	Ratio	mW $cm^{-2}sr^{-1}$	Ratio	%	Ratio
Band 4	42		0.820		0.195	
		0.66		0.81		0.69
Band 5	64		1.008		0.281	
		0.98		1.12		0.91
Band 6	65		0.901		0.308	
		2.60		0.57		1.145
Band 7	25		1.587		0.269	

TABLE 4. CALIBRATION OF THE FOUR SPECTRAL BANDS FOR LANDSATS 1, 2, AND 3

	Digital Value	Landsat 1		Landsat 2 Prior to 7/16/75		Landsat 2 After 7/16/75		Landsat 3 Prior to 6/1/78		Landsat 3 After 6/1/78	
	(D_n)	Radiance	Reflectance	Radiance	Reflectance	Radiance	Reflectance	Radiance	Reflectance	Radiance	Reflectance
Band 4	42	0.820	0.195	0.761	0.181	0.923	0.220	0.754	0.180	0.883	0.210
Band 5	64	1.008	0.281	0.821	0.229	0.917	0.255	0.897	0.250	0.917	0.250
Band 6	65	0.901	0.308	0.751	0.257	0.807	0.276	0.757	0.259	0.777	0.266
Band 7	25	1.587	0.269	1.731	0.294	1.618	0.274	1.768	0.300	1.538	0.261

user than are the digital values. It is much easier to mentally visualize a reflectance of 0.28 in Band 5 than to visualize a D_n of 64, for example.

In addition to the factor of physical significance, incorrect conclusions may be drawn by using the digital numbers alone. If one is classifying a single Landsat scene, the problem is not severe because the digital values are internally consistent on a relative basis. But if one is ratioing bands within a single scene, the resultant values can quantitatively be incorrect because the calibration of each band is different. Consider a pixel in a Landsat 1 scene with digital values in the four bands of 42, 64, 65, and 25 with a solar elevation of 48° (an actual example). Table 3 shows the values of the digital and physical values and the ratios of adjacent bands.

If one wishes to develop "spectral signatures" (a most difficult and complex concept) and to compare data from different sensors at different times and at different sun angles, the only meaningful figure is the actual reflectance of the terrain that has been calculated and corrected for all the systematic variables in the data collection and processing system.

The example above is expanded in Table 4 to show the effect of the difference in calibration of the multispectral scanners on Landsats 1, 2, and 3. The pixel values (D_n in each band) and the sun angle (48°) from a Landsat scene in western Utah are used to compute radiance and reflectance.

DISCUSSION

A study of Table 4 reveals significant differences in radiance and reflectance that are caused solely by the difference in calibration of the multispectral scanners. For example, the reflectance in band 6 ranges from 0.257 to 0.308 with a mean of 0.273 and a standard deviation of 0.021. This example shows that Landsat digital image analysis should not be conducted solely on the basis of the digital values on the computer-compatible tape. If two corresponding pixels have the same digital values in different data sets, they will be classified as the same features. However, if the actual terrain reflectance is different, the pixels should be placed in different classes (if the differences in reflectance exceed the selected variance). The reverse is also true; two pixels with the same reflectivity in all bands will be represented by different digital values in the two data sets and will be classed differently when they actually are identical.

From the foregoing arguments, it can be seen that the digital values should be corrected to radiance or reflectance as required by the analysis, before going further. The particular analytical conditions for which conversion should be done are (1) band ratioing, (2) analysis of a digital mosaic of two or more scenes in which sun angles are different, (3) analysis of a mosaic of two or more scenes taken by two or more Landsats or before and after a change in scanner calibration of a single Landsat, and (4) comparison or detection of change between two or more images taken under conditions of different sun angles and different calibrations.

The conversion requires that computational algorithms be available on the computer and that the first step in analysis be to convert the digital values to reflectance. After conversion, standard classification algorithms can be used without modification.

It would be worthwhile for the digital data to be supplied on computer-compatible tapes in the form of radiance values rather than the present digital values. This approach would require an additional step in the preprocessing, that of calculating the radiance of each pixel from its digital value and from the calibration of the scanner at the time of imaging. The result would be a consistent terrain-atmosphere dependent physical value as the basic data rather than its variable system-related analog. This processing would eliminate the need for calibrating each data set to be analyzed. A disadvantage of this technique is that it would require more tape storage because images would have to be stored as real rather than byte images. As an alternative, tapes could be supplied in the present digital format with the calibration data in the tape header so that the information would be available for further processing.

The above argument has (for simplicity) neglected other important factors, that of correction for atmospheric absorption, atmospheric scattering, and the radiance effects of nearby pixels (adjacency effects). Corrections for these factors may be done with simplified models (such as dark level subtraction for an atmospheric scattering correction) or in a highly sophisticated manner (such as the use of radiosonde observations at the time of imaging in order to determine the state of the atmosphere). In order to arrive at a true measure of terrain reflectance, such atmospheric corrections must be done. The required measurement methods and models are, however, beyond the scope of this paper. The analyst must recongize that, without an atmospheric correction to his data, he is analyzing the Earth-atmosphere system, rather than the Earth alone. In many cases he must assume that the atmosphere is uniform over the area in an entire Landsat image or that it is identical during two Landsat passes.

In summary, as users become more aware of and dependent on the quantitative physical relationships expressed in Landsat data, they must reconsider the system-related inconsistencies in the original data.

Proper and consistent use of Landsat digital data require that the digital numbers from computer-compatible tapes be converted to quantitative physical values such as radiance (as measured at satellite altitude) or reflectance of the ground (or albedo of the ground). Failure to do so, especially when ratioing bands, mosaicing images, classifying multiple images, or detecting changes over time, will produce incorrect and misleading results.

Computer-compatible tapes of Landsat image data should be provided with the digital values converted to radiance by applying the scanner calibration or, alternatively, by providing the calibration data in the tape header so that it is readily available to the analyst.

Reference

U.S. Geological Survey, 1979, *Landsat Data Users Handbook* (revised): U.S. Geological Survey, pp. 1-1 to 10-1, appendix.

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